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DATA AVAILABILITY, DATA QUALITY IN LCA

# Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) $CO_2$PE! initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies

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**Abstract**
*Purpose* This report presents two case studies, one for both the screening approach and the in-depth approach, demonstrating the application of the life cycle assessment-oriented methodology for systematic inventory analysis of the machine tool use phase of manufacturing unit processes, which has been developed in the framework of the $CO_2$PE! collaborative research programme ($CO_2$PE! 2011) and is described in part 1 of this paper (Kellens et al. 2011).

*Screening approach* The screening approach, which provides a first insight into the unit process and results in a set of approximate LCI data, relies on representative industrial data and engineering calculations for energy use and material loss. This approach is illustrated by means of a case study of a drilling process.

*In-depth approach* The in-depth approach, which leads to more accurate LCI data as well as the identification of potential for environmental improvements of the manufac-

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Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory. Part 1: methodology description [Int J Life Cycle Assess doi:10.1007/s11367-011-0340-4]—Part 2: case studies [Int J Life Cycle Assess doi:10.1007/s11367-011-0352-0]
Preamble. The $CO_2$PE! UPLCI– initiative aims to document and improve the environmental impact created during the use phase of a wide range of discrete part manufacturing processes. In addition to the first article, which describes the developed methodology comprising two approaches with different levels of detail, this paper provides for both approaches a case study of the Life Cycle Inventory step.

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turing unit processes, is subdivided into four modules, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process in- and outputs are measured and analysed in detail. The procedure of this approach, together with the proposed $CO_2$PE! template, is illustrated by means of a case study of a laser cutting process.

*Results* The $CO_2$PE! methodology aims to provide high-quality LCI data for the machine tool use phase of manufacturing unit processes, to be used in life cycle inventory databases and libraries, as well as to identify potential for environmental improvement based on the in-depth analysis of individual manufacturing unit processes. Two case studies illustrate the applicability of the methodology.

**Keywords** $CO_2$PE! · Drilling · Energy and resource efficiency · Laser cutting · Unit process life cycle inventory (UPLCI)

## 1 Introduction

The $CO_2$PE! initiative ($CO_2$PE! 2011) has as an objective to coordinate international efforts aiming to document and analyse the environmental impacts of the machine tool use phase of a wide range of current and emerging manufacturing processes, and to provide guidelines to reduce these impacts. A proposed two-level life cycle inventory (LCI) approach is aimed at both providing manufacturing unit process datasets for life cycle analyses (LCA) of products and at supporting the diagnosis and optimization of the environmental impact of specific manufacturing unit processes towards machine tool designers.

This paper focuses on the practical documentation of the data collection phase (step C) of the $CO_2$PE! methodology described in the part 1 of this paper (Kellens et al. 2011). As shown in Fig. 1, this step starts with a goal and scope definition as required by ISO14040 (2006) and ISO14044 (2006). The actual LCI data collection effort (step $C_2$) consists of two alternative approaches with different levels of detail.

The screening approach (illustrated by a case study of a drilling process in Section 2) provides a first insight in the unit process and results in a set of approximate LCI data, which can be used as starting point for the in-depth approach. It relies on representative general data and theoretical calculations for energy use and material loss.

The in-depth approach (illustrated by a case study of a laser cutting process in Section 3) provides more accurate and complete LCI data, to be used in LCI databases, and will help to identify potential improvement of the involved manufacturing unit processes. As shown in Fig. 1, the in-depth approach is subdivided into four parts, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process in- and outputs are measured and analysed in detail.

## 2 Screening approach

In this case study the life cycle inventory (UPLCI) of the use phase of a drilling machine tool is presented with the energy and resource consumption calculations analysed using the screening approach. In order to simulate an industrial shop floor, processing a wide variety of part geometries and sizes with a limited number of machine tools, a medium-sized machine tool (JVH 1500, JEENXI Technology Co., Ltd. 2010) is selected for this case study. The complete machine tool specifications are listed in the full case study which can be found in the online supporting information and at UPLCI (2011; ESM 2, Appendix II).

### 2.1 General process information

#### *2.1.1 Objective and product details*

The workpiece (grey cast iron, BHN 180) is a square block of dimensions $100\times100\times50$ mm ($L\times W\times H$) as shown in Fig. 2. The objective of this case study is to analyse the energy and resource consumption in drilling four regularly spaced holes of 19.1 mm diameter through the thickness of the workpiece. The weight of the workpiece is 3.6 kg.

#### *2.1.2 Machining process*

During the drilling process, the tool is considered to be at an offset of 5.7 mm (0.3 times the diameter of the tool) above the workpiece. Every time while drilling a hole, the tool comes down from a height of 5.7 mm before drilling a hole. For a 50-mm workpiece thickness, it retracts 61.4 mm (5.7+50+5.7) from the overtravel position (5.7 mm below) back to the offset position (5.7 mm above) after completing the drilling cycle. The cutting parameters such as feeds and speeds are listed in Table 1.

### 2.2 LCI energy calculations

#### *2.2.1 Time, power and energy calculations per hole*

The total processing time can be divided into the three subgroups of basic time (standby), idle time (partial mode) and drilling time (full mode).

#### 2.2.2 Drilling time

The time for drilling or enlarging a through hole of length 50 mm is determined by

$$t_{\mathrm{drilling}}[\mathrm{min}] = d/(f \times N) = d/f_{\mathrm{r}}$$

where $d$ is the workpiece thickness of the given hole in millimetres, $f$ is the feed in millimetres/revolution and $N$ is the drill rotational speed in revolutions/minute.

$$t_{\mathrm{drilling}} = 50/111 = 0.45\ \mathrm{min/hole} = 27\ \mathrm{s/hole}$$

The machining power for each hole is

$$P_{\mathrm{drilling}}[\mathrm{kW}] = \mathrm{VRR} \times \mathrm{specific\ cutting\ energy}$$

The volume removal rate (VRR)=31,800 mm$^3$/min=530 mm$^3$/s and the specific cutting energy=1.3 J/mm$^3$.

$$P_{\mathrm{drilling}} = 530 \times 1.3 = 0.69\ \mathrm{kW}$$

The tip energy required per hole is

$$E_{\mathrm{drilling}} = P_{\mathrm{drilling}} \times t_{\mathrm{drilling}} = 0.69 \times 27 = 18.6\ \mathrm{kJ/hole}$$

#### 2.2.3 Handling time

In between workpieces, the drill retracts to a home position 25 mm above the approach point (which is 5.7 mm above the workpiece) to be used when drilling holes. The time required for the cutter to move from home position to approach point (25 mm) is essentially determined by drilling in air.

The air time of the rapid traverse speed (VTR) to approach is

$$t_{\mathrm{a1}} = 25/\mathrm{traverse\ speed} = 25/24{,}000\ \mathrm{mm/min}$$
$$= 0.001\ \mathrm{min} = 0.06\ \mathrm{s(negligible)}$$

The air time for a single hole, over and above cutting the workpiece, is the approach plus the over travel distance which are repeated when the drill retracts.

The handling distances are (approach + overtravel) + (retraction)

$$= (0.3D + 0.3D) + (0.3D + 50\ \mathrm{mm\ thickness} + 0.3D)$$

The partial mode or idle time is determined

$$t_{\mathrm{a}} = [0.3 \times D + 0.3 \times D]/(f_{\mathrm{r}}) + [0.3D + d + 0.3D]/\mathrm{VTR}$$
$$t_{\mathrm{a}} = [0.3 \times 19.1 + 0.3 \times 19.1]/(111) + [5.7 + 50 + 5.7]/24{,}000 = 0.106\ \mathrm{min} = 6.3\ \mathrm{s}$$

For a single hole, there is no traverse (HTR) to other workpiece holes.

The idle power of the machine can be calculated based on the individual power specifications of the machine.

$$P_{\mathrm{idle}} = P_{\mathrm{spindle}} + P_{\mathrm{coolant}} + P_{\mathrm{axis}}$$

Based on the nominal data from the CNC drilling machine tool builder, the assumed values are

$$P_{\mathrm{coolant}} = 1\ \mathrm{kW}(\sim 1.5\ \mathrm{hp}); P_{\mathrm{spindle}} = 4\ \mathrm{kW}(\sim 5\ \mathrm{hp}); P_{\mathrm{axis}} = 5\ \mathrm{kW}(\sim 7\ \mathrm{hp}).$$

Therefore the idle power for the process is

$$P_{\mathrm{idle}} = P_{\mathrm{spindle}} + P_{\mathrm{coolant}} + P_{\mathrm{axis}} = 4 + 1 + 5 = 10\ \mathrm{kW}$$

The total idle time for one hole, being the time during which $P_{\mathrm{idle}}$ was to be supplied is

$$t_{\mathrm{idle}} = t_{\mathrm{a}} + t_{\mathrm{drilling}} = 6.3 + 27 = 33.3\ \mathrm{s}$$

In this time, the actual drilling time is included since the idle power also has to be supplied during processing.

Total energy during the idle process per hole is

$$E_{\mathrm{idle}} = P_{\mathrm{idle}} \times t_{\mathrm{idle}} = 10 \times 33.3 = 333\ \mathrm{kJ/hole}$$

#### 2.2.4 Load/unload time

The total basic time for this case study can be determined based on the following assumptions:

- The work holding device used for clamping the workpiece is a simple vise, so the total time required to mount the workpiece on the vise manually is 9.3 s (Fridriksson 1979).
- After completing the drilling process on a single workpiece, the machine is cleaned using pneumatic cleaners or air blowers. The time required to clean the machine tool is assumed to be 25.4 s.
- The machined part has to be removed manually from the fixture. The time required to remove the material from the fixture is assumed to be 9.3 s.

Therefore the load/unload time for this study is

$$t_{\mathrm{l/u}} = \mathrm{loading\ time} + \mathrm{cleaning\ time} + \mathrm{unloading\ time}$$
$$= 9.3 + 25.4 + 9.3 = 44\ \mathrm{s}$$

Basic power of the machine can be assumed as 25% of the machine maximum (30 kW) in the manufacturer specifications. Therefore the power consumed during the basic process ($P_{\mathrm{basic}}$)=7.5 kW.

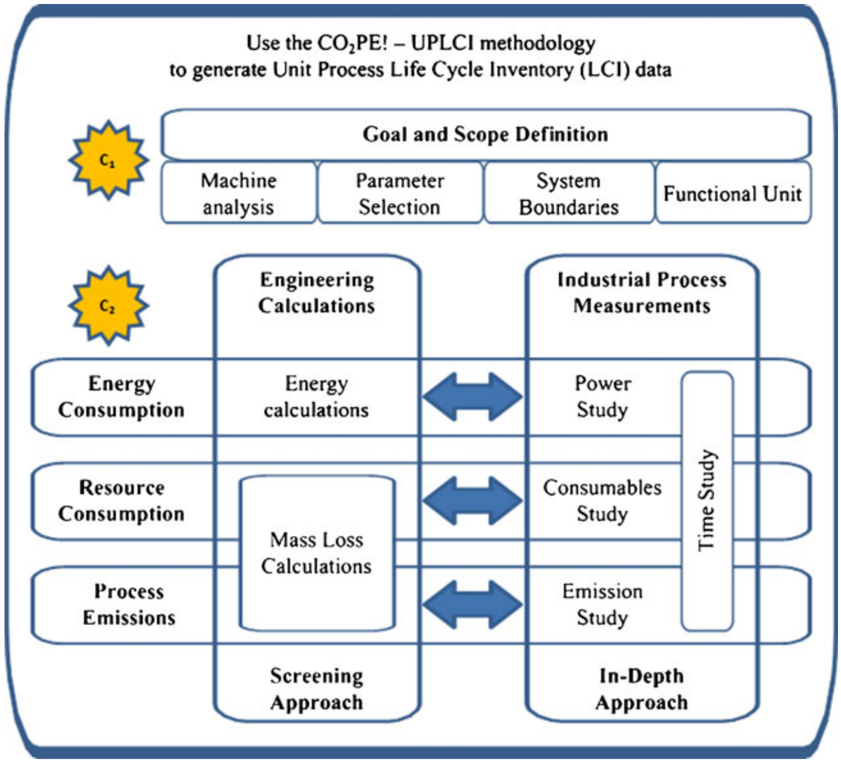



**Fig. 1** Overview of the LCI step of the $CO_2$PE!–UPLCI framework

Energy consumed during this process is

$$E_{\text{basic}} = P_{\text{basic}} \times t_{\text{basic}}$$

The basic time for the process to drill one hole can be taken as the sum of idle time (which contains the machining time) and load/unload times, i.e.,

$$t_{\text{basic}} = t_{\text{l/u}} + t_{\text{idle}} = 44 + 33.3 = 77.3\ \text{s}$$

$$E_{\text{basic per hole}} = 7.5 \times 77.3 = 579.7\ \text{kJ per hole}$$

Total energy required for drilling one hole can be determined as

$$E_{\text{process}} = E_{\text{drilling}} + E_{\text{idle}} + E_{\text{basic}} = 18.6 + 333 + 579.3$$

$$= 930.9\ \text{kJ/one hole}$$

Average total power required for machine utilization during drilling per hole is

$$P_{\text{mtotal}} = E_{\text{process}}/t_{\text{total}} = 930.9/77.3 = 12.0\ \text{kW}.$$

## 2.3 LCI mass loss calculations

### *2.3.1 Waste material loss*

Volume of the material removed from a hole $= V_{\text{removal}} = \frac{\pi D^2}{4} \times d = 14,326\ \text{mm}^3$

Chip mass $(m_s) = V_{\text{removal}} \times \rho$

$$m_s = 14,326 \times 7,300 \times 10^{-9} = 0.10\ \text{kg/hole}$$

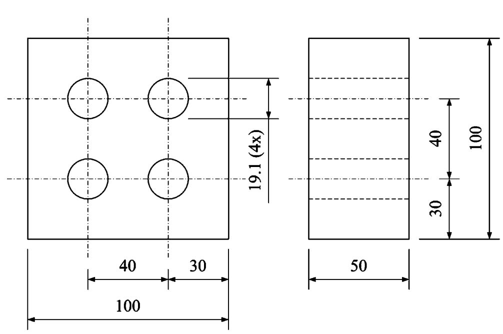



**Fig. 2** Dimensions (in millimetres) of the workpiece

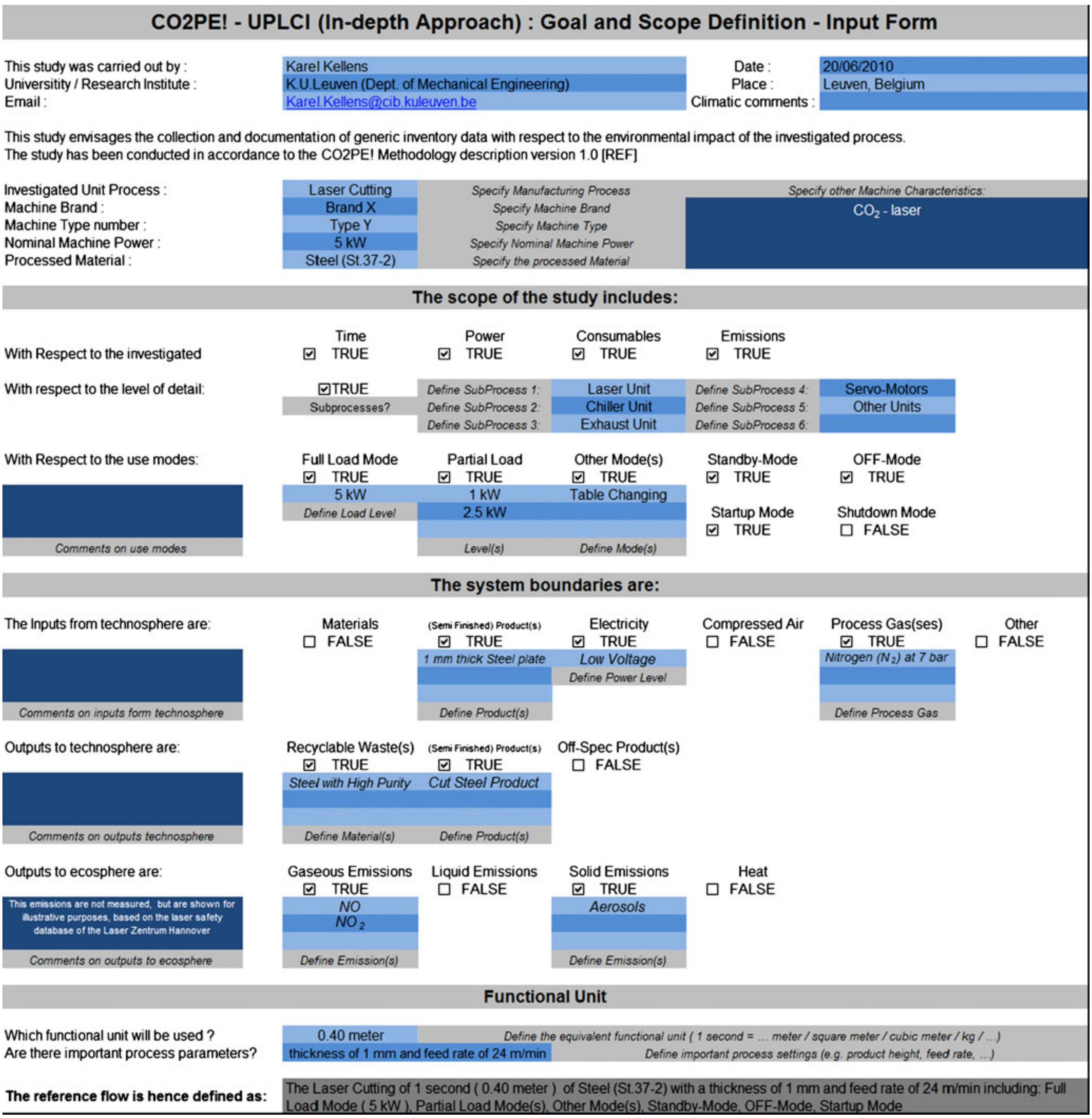
**Table 1** Cutting parameters

| | |
|---|---|
| Drill diameter ($D$) | 19.1 mm |
| Cutting speed ($v$) | 25 m/min |
| Feed ($f$) | 0.267 mm/rev |
| Spindle speed ($N$)=$v/\pi D$ | 417 rpm |
| Feed rate ($f_r$)=$f \times N$ | 111 mm/min |
| VRR=$(\pi D^2/4)f_r$ | 31,800 mm$^3$/min |
| Depth of hole | 50 mm |
| Rapid horizontal traverse rate (horizontal, X, Y) | 30 m/min |
| Rapid vertical traverse rate (vertical, Z) | 24 m/min |

*2.3.2 Cutting fluid waste*

According to Clarens et al. (2008), a single CNC machine tool using cutting fluid requires an individual pump to circulate the fluid from a 55-gal (208 l) tank to the cutting zone. The 208-l/machine tool is reused within the process until it is disposed off after 2 weeks. The cutting fluid is used during the actual drilling operation, which takes about 102 h/week, so the cutting fluid loss is 208 l/(204×60) per min, which is 0.017 l/min or about 17 g/min.

The coolant, which is a mixture of water and oil, is about 70–95 wt.% water, so at 85 wt.% water, the oil loss is 15 wt.% or 2.5 g oil/min (0.042 g/s). Since the drilling time per hole ($t_m$) is 27 s, the mass loss of the coolant=0.042× 27=1.1 g oil/hole. The fugitive loss is 0.1 g cutting oil/min or 0.045 g cutting oil/hole.



CO2PE! - UPLCI (In-depth Approach) : Goal and Scope Definition - Input Form

This study was carried out by : Karel Kellens — Date : 20/06/2010
University / Research Institute : K.U.Leuven (Dept. of Mechanical Engineering) — Place : Leuven, Belgium
Email : Karel.Kellens@cib.kuleuven.be — Climatic comments :

This study envisages the collection and documentation of generic inventory data with respect to the environmental impact of the investigated process.
The study has been conducted in accordance to the CO2PE! Methodology description version 1.0 [REF]

| | | | |
|---|---|---|---|
| Investigated Unit Process : | Laser Cutting | Specify Manufacturing Process | Specify other Machine Characteristics: $CO_2$ - laser |
| Machine Brand : | Brand X | Specify Machine Brand | |
| Machine Type number : | Type Y | Specify Machine Type | |
| Nominal Machine Power : | 5 kW | Specify Nominal Machine Power | |
| Processed Material : | Steel (St.37-2) | Specify the processed Material | |

The scope of the study includes:

With Respect to the investigated: Time ☑ TRUE; Power ☑ TRUE; Consumables ☑ TRUE; Emissions ☑ TRUE

With respect to the level of detail: ☑TRUE Subprocesses?
Define SubProcess 1: Laser Unit; Define SubProcess 2: Chiller Unit; Define SubProcess 3: Exhaust Unit; Define SubProcess 4: Servo-Motors; Define SubProcess 5: Other Units; Define SubProcess 6:

With Respect to the use modes: Full Load Mode ☑ TRUE, 5 kW (Define Load Level); Partial Load ☑ TRUE, 1 kW, 2.5 kW (Level(s)); Other Mode(s) ☑ TRUE, Table Changing (Define Mode(s)); Standby-Mode ☑ TRUE; OFF-Mode ☑ TRUE; Startup Mode ☑ TRUE; Shutdown Mode ☐ FALSE
Comments on use modes

The system boundaries are:

The Inputs from technosphere are: Materials ☐ FALSE; (Semi Finished) Product(s) ☑ TRUE, 1 mm thick Steel plate (Define Product(s)); Electricity ☑ TRUE, Low Voltage (Define Power Level); Compressed Air ☐ FALSE; Process Gas(ses) ☑ TRUE, Nitrogen ($N_2$) at 7 bar (Define Process Gas); Other ☐ FALSE
Comments on inputs form technosphere

Outputs to technosphere are: Recyclable Waste(s) ☑ TRUE, Steel with High Purity (Define Material(s)); (Semi Finished) Product(s) ☑ TRUE, Cut Steel Product (Define Product(s)); Off-Spec Product(s) ☐ FALSE
Comments on outputs technosphere

Outputs to ecosphere are: Gaseous Emissions ☑ TRUE, NO, $NO_2$ (Define Emission(s)); Liquid Emissions ☐ FALSE; Solid Emissions ☑ TRUE, Aerosols (Define Emission(s)); Heat ☐ FALSE
This emissions are not measured, but are shown for illustrative purposes, based on the laser safety database of the Laser Zentrum Hannover
Comments on outputs to ecosphere

Functional Unit

Which functional unit will be used ? 0.40 meter — Define the equivalent functional unit ( 1 second = ... meter / square meter / cubic meter / kg / ...)
Are there important process parameters? thickness of 1 mm and feed rate of 24 m/min — Define important process settings (e.g. product height, feed rate, ...)

**The reference flow is hence defined as:** The Laser Cutting of 1 second ( 0.40 meter ) of Steel (St.37-2) with a thickness of 1 mm and feed rate of 24 m/min including: Full Load Mode ( 5 kW ), Partial Load Mode(s), Other Mode(s), Standby-Mode, OFF-Mode, Startup Mode

**Fig. 3** Input form for the laser cutting case

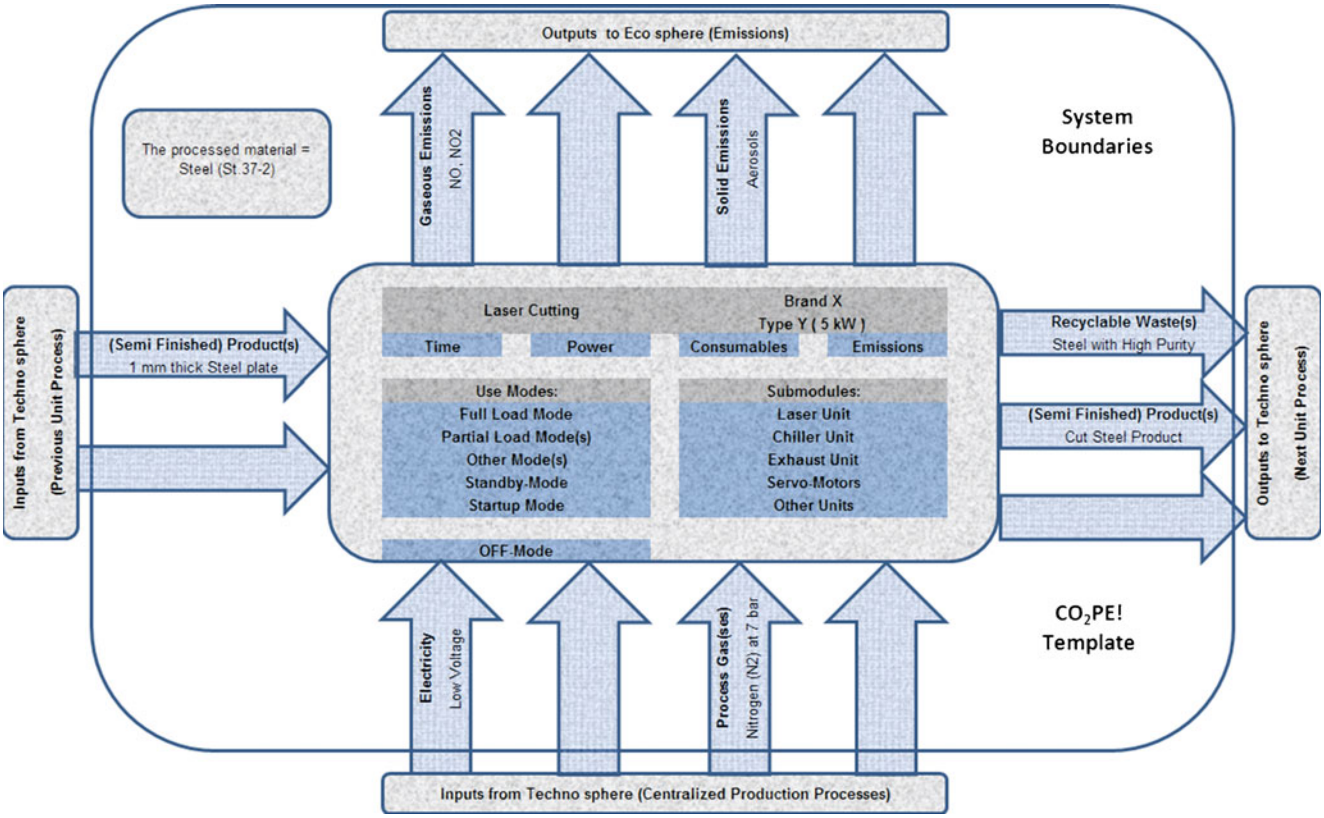



**Fig. 4** Schematic overview of the system boundaries for the laser cutting case

*2.3.3 UPLCI case study summary*

This example presents the models, approaches and measures used to represent the environmental impact of drilling unit operations referred to as the unit process life cycle inventory. The four major environmental-based results are energy consumption, metal chips removed, cutting fluid and lubricant oil. With only the following information, the unit process life cycle energy for drilling can be estimated for a given job:

1. Material of part being manufactured,
2. Diameter, number of holes, and location,
3. Hole depth to be drilled and
4. Loading/unloading time (see full UPLCI)

**Table 2** Production tasks and relative time distribution

| | Task | Time (%) |
|---|---|---|
| A | Cutting | 85.2 |
| B | Changing tables | 5.6 |
| C | Loading program | 3.6 |
| D | Changing laser head | 0.4 |
| E | Checking products | 4.4 |
| F | Standstill | 0.8 |

The life cycle inventory effort of the use phase of drilling is based on a typical high production scenario (on a CNC drilling machine) to reflect industrial manufacturing practices.

## 3 In-depth approach

In this section, the in-depth approach is demonstrated by a case study of a laser cutting process. Furthermore, the use of the $CO_2$PE! template is illustrated by means of this example.

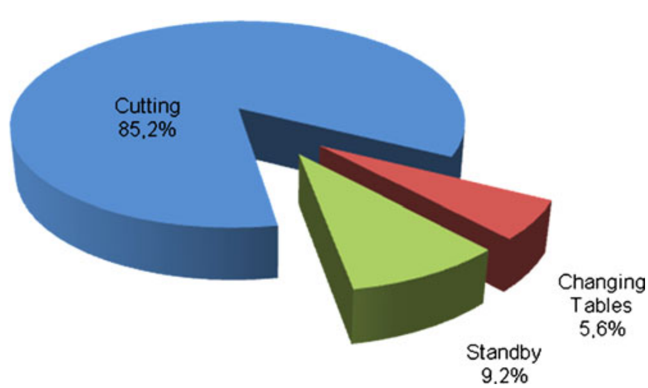



**Fig. 5** Time consumption in different production modes

**Table 3** Power consumption measurements (in kilowatts) of the sub-processes in each production mode

| | Laser source | Chiller | Exhaust system | Servos | Other | Total |
|---|---|---|---|---|---|---|
| Off mode | 0.82 | 0.84 | 0 | 0.28 | 0.13 | 2.07 |
| Start-up | 16.5 | 6.07 | 0 | 0.28 | 0.13 | 22.98 |
| Standby | 19.5 | 7.24 | 0 | 0.28 | 0.13 | 27.15 |
| Cutting (5 kW) | 32.7 | 11 | 2.92 | 0.86 | 0.13 | 47.61 |
| Cutting (2.5 kW) | 30.8 | 11 | 2.92 | 0.86 | 0.13 | 45.71 |
| Cutting (1 kW) | 27.4 | 11 | 2.92 | 0.86 | 0.13 | 42.31 |
| Changing tables | 19.5 | 7.24 | 0 | 0.74 | 0.13 | 27.61 |

### 3.1 Goal and scope definition

First the goal and scope (machine analysis, parameter selection, system boundaries and functional unit) of the study are clearly defined. The completed input form and created schematic overview ($CO_2$PE! template, ESM 1; available as electronic supplementary material) of the system boundaries for the case study are shown in Figs. 3 and 4, respectively.

As shown in Fig. 3, the reference flow of the intended study is automatically defined at the bottom of the input form. First of all, the investigated process as well as the generally applicable reference flow (1 s of processing time) and the corresponding functional unit are indicated. Important settings and process parameters are shown, and finally, all included production modes are presented.

### 3.2 Life cycle inventory

As described in part 1 (Kellens et al. 2011) of this paper and shown in Fig. 1, the LCI step of the in-depth approach consists of four parts, including a time study, a power consumption study, a consumables study and an emission study. These four studies, in which all relevant process in- and outputs are measured and analysed in detail, are presented below for a case study on the use phase of a laser cutting machine tool.

#### *3.2.1 Time study*

Laser cutting operations were observed for multiple batches in different companies using camera monitoring. As shown in Table 2, based on these observations, six different production tasks are distinguished for the laser cutting process. The actual cutting process is responsible for more than 85% of the total time. The remaining time is split up between table changing, program loading, checking products and other short activities. Since tasks C until F all represent the standby mode of the laser cutting machine tool, ultimately three different production modes are distinguished as shown in Fig. 5.

#### *3.2.2 Power study*

The power measurements for all identified sub-processes during the three productive production modes as well as the non-productive modes are listed in Table 3 and shown in Fig. 6. The investigated machine tool is equipped with a winter-off mode in which freezing of the laser cooling unit is avoided by continuously heating and circulating of the coolant. Together with the transformer losses, this results in an energy consumption of 2.07 kW during off mode.

For an overview of the energy consumption for the reference flow of 1 s of effective cutting, the results of the time measurements are combined with the power measurements as described in Eq. 1 in part 1 of this paper (Kellens et al. 2011). The energy consumption in non-productive modes (off mode and standby mode) is calculated and divided over the actual processing time (2,000 h/year). There is a machine tool start-up (12 min) every day before the 8-h shift starts. Table 4 shows the energy consumption per second of effective cutting (in kilowatt hour/second) for three different loads (5, 2.5 and 1 kW).

#### *3.2.3 Consumables study*

*Cutting gas: nitrogen* A first input from the techno sphere is the required cutting gas, which is used as assist gas

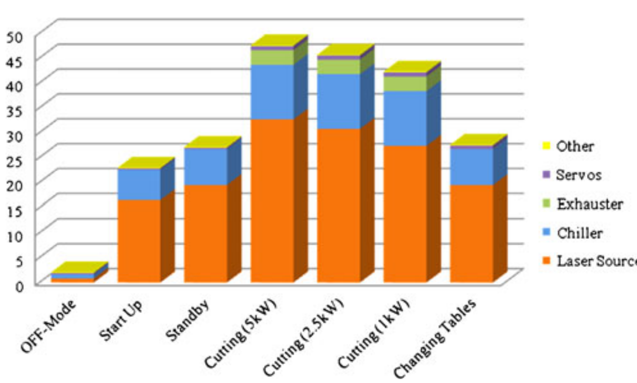



**Fig. 6** Overview of the power consumption (in kilowatts) of the sub-processes in each production mode

**Table 4** Energy consumption per second (in kilowatt hour/second) for different loads

| | Power (kW) | Time (%) | Time (sec) | Energy (kWh/s) | Energy (%) |
|---|---|---|---|---|---|
| Standby | 27.15 | 9.2 | 0.108 | 0.0008 | 4.9 |
| Cutting (5 kW) | 47.61 | 85.2 | 1.000 | 0.0132 | 79.5 |
| Changing tables | 27.61 | 5.6 | 0.066 | 0.0005 | 3.0 |
| Extra (off mode and start-up) | | | | 0.0021 | 12.6 |
| Total | – | 100 | 1.174 | 0.0166 | 100 |
| Standby | 27.15 | 9.2 | 0.108 | 0.0008 | 5.1 |
| Cutting (2.5 kW) | 45,71 | 85.2 | 1.000 | 0.0127 | 78.8 |
| Changing tables | 27.61 | 5.6 | 0.066 | 0.0005 | 3.1 |
| Extra (off mode and start-up) | | | | 0.0021 | 13.0 |
| Total | – | 100 | 1.174 | 0.0161 | 100 |
| Standby | 27.15 | 9.2 | 0.108 | 0.0008 | 5.4 |
| Cutting (1 kW) | 42.31 | 85.2 | 1.000 | 0.0118 | 77.5 |
| Changing tables | 27.61 | 5.6 | 0.066 | 0.0005 | 3.3 |
| Extra (off mode and start-up) | | | | 0.0021 | 13.8 |
| Total | – | 100 | 1.174 | 0.0152 | 100 |

during the laser cutting process. Depending on the material and desired quality of the cut, oxygen, nitrogen ($N_2$) and compressed air are often used as cutting gas (Serruys 2002). For this case study, $N_2$ is applied as the cutting gas. Based on the plate thickness, there are three levels of $N_2$ flow rate as shown in Fig. 7. For the laser cutting of a 1-mm-thick plate, a flow rate of 16 $m^3/h$ is used.

*Recyclable solid waste* During the laser cutting process, an amount of solid waste is created as output to the techno sphere. This waste is steel with high purity and thus well recyclable. Since the generation of waste is not a production time-related issue, it is described as a percentage of the input material. For this case study, we found a nesting efficiency of 86.5%. Of course this nesting efficiency will be strongly influenced by the part geometry or combination of clustered part geometries. For laser cutting operations, nesting efficiencies typically range from 80% to 90% with a maximum around 95% for optimally nested (semi-) rectangular parts.

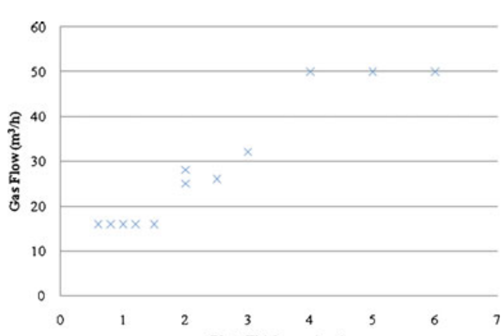



**Fig. 7** Flow rate for $N_2$ as a function of the plate thickness (Serruys 2002)

*3.2.4 Emission study*

For this case study, the emission rates are given based on measurements performed by the Laser Zentrum Hannover which are accessible in their online safety database (LZH 2011). The sampling took place in a special cubicle in the exhaust duct in which the aerosols were isokinetically extracted using probes (Haferkamp et al. 1992). Table 5 shows the emission rates for aerosols and gaseous emissions of NO and $NO_2$. The aerosols mainly consist of metal oxides in which elements with low evaporation temperature (e.g. zinc, manganese) are over-represented (Haferkamp et al. 1999). Figure 8 shows the results sheet generated with the $CO_2$PE! template based on the goal and scope definition input form shown in Fig. 3.

## 3.3 LCI datasets

By merging and comparing unit process datasets, such as described in Section 3.2, of similar machine tools of

**Table 5** Emission rates

| Emission | Rate (mg/s) |
|---|---|
| NO | 0.0023 |
| $NO_2$ | 0.0029 |
| Aerosols | 1.1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| average value | Laser Cutting | | | | | | | | | | |
| unit | | | | | | | | | | | |
| not adaptable | Full Load Mode | Partial Load Mode(s) | | | Other Mode(s) | | | Standby-Mode | Startup Mode | | OFF-Mode |
| | 5 kW | 1 kW | 2.5 kW | | Table Changing | | | | | | |
| | General Inputs from Technosphere | | | | | General Outputs to Technosphere | | | | | |
| | | | Electricity: | | | Recyclable Waste(s): | | (Semi Finished) Product(s): | | | |
| | | | 1 mm thick Steel plate | 7,8 | | Steel with High Purity | 13,5 | Cut Steel Product | 1,05 | | |
| | | | | kg | | | % of Input Material | | kg | | |
| Comments on measurements | | | | | | | | | | | |
| Time Measurements | | | | | | | | | | | |
| Time Measurements | 85,2 | 85,2 | 85,2 | | 5,6 | | | 9,2 | 720 | | |
| | % Processing Time | % Processing Time | % Processing Time | | % Processing Time | | | % Processing Time | Seconds | | |
| Power Measurements | | | | | | | | | | | |
| Energy consumption of functional unit : | 0,01663 | 0,01610 | 0,01516 | | | | | | | | |
| | (kWh / s) | (kWh / s) | (kWh / s) | | | | | | | | |
| Machine Power Level : | 47,6100 | 45,7100 | 42,3100 | | 27,61 | | | 27,15 | 22,98 | | 2,07 |
| | (kW) | (kW) | (kW) | | (kW) | | | (kW) | (kW) | | (kW) |
| Power of SubProcesses: | | | | | | | | | | | |
| Laser Unit | 32,7 | 30,8 | 27,4 | | 19,5 | | | 19,5 | 16,5 | | 0,82 |
| Chiller Unit | 11 | 11 | 11 | | 7,24 | | | 7,24 | 6,07 | | 0,84 |
| Exhaust Unit | 2,92 | 2,92 | 2,92 | | 0 | | | 0 | 0 | | 0 |
| Servo-Motors | 0,86 | 0,86 | 0,86 | | 0,74 | | | 0,28 | 0,28 | | 0,28 |
| Other Units | 0,13 | 0,13 | 0,13 | | 0,13 | | | 0,13 | 0,13 | | 0,13 |
| | (kW) | (kW) | (kW) | | (kW) | | | (kW) | (kW) | | (kW) |
| Consumable Measurements | | | | | | | | | | | |
| Process Gas(ses): | | | | | | | | | | | |
| Nitrogen (N2) at 7 bar | 0,0044 | 0,0044 | 0,0044 | | 0 | | | 0 | 0 | | 0 |
| | $m^3$ / s | m3 / s | m3 / s | | m3 / s | | | m3 / s | m3 / s | | m3 / s |
| Emission Measurements | | | | | | | | | | | |
| Gaseous Emissions: | | | | | | | | | | | |
| NO | 0,0023 | 0,0023 | 0,0023 | | 0 | | | 0 | 0 | | 0 |
| | mg / s | mg / s | mg / s | | mg / s | | | mg / s | mg / s | | |
| NO2 | 0,0029 | 0,0029 | 0,0029 | | 0 | | | 0 | 0 | | 0 |
| | mg / s | mg / s | mg / s | | mg / s | | | mg / s | mg / s | | mg / s |
| Solid Emissions: | | | | | | | | | | | |
| Aerosols | 1,1 | 1,1 | 1,1 | | 0 | | | 0 | 0 | | 0 |
| | mg / s | mg / s | mg / s | | mg / s | | | mg / s | mg / s | | mg / s |

**Fig. 8** Results for the laser cutting case study in the $CO_2PE$! template

different suppliers and capacities provided by different $CO_2PE$ partners, generic unit process datasets and related parametric models will be generated based on the average values of the different studies. Where relevant, further divisions (process capacities, material…) per manufacturing unit process will be made. Based on the reference flow of 1 s of processing time for a specified load level of a unit manufacturing process for a specified material, based on a working scheme of 2,000 h/year (Kellens et al. 2011), all documented in- and output flows (consumptions) will be linked to available LCI datasets from LCI databases, covering the full life cycle, starting from the raw materials extraction to the end of life treatment, of the considered process in- and outputs.

Wherever possible, the complete and accurate data from the in-depth approach are used to develop the generic unit process datasets. In case in-depth analyses are not (fully) available, datasets from the screening approach could be used to replace the missing parts, provided that each step is

clearly described and documented. In order to be compatible with current public as well as commercial LCI databases, the generic unit process datasets will be offered in the EcoSpold data format (EcoSpold 2011), which is the most widespread LCI data exchange format worldwide, supported by all leading LCA software tools.

## 4 Conclusions and outlook

By providing a well defined methodology (Kellens et al. 2011), the authors aim to give an impetus to the generation of uniform, complete and robust LCI datasets of the machine tool use phase of unit manufacturing processes. In order to demonstrate the practical procedure of the life cycle inventory step (step C) of the methodology, a case study is presented for both approaches. While the screening approach is demonstrated for a drilling process, the in-depth approach is applied on a laser cutting process.

By repeating this study for a range of similar machines (several suppliers and machine capacities), parametric impact estimation models and eco-design rules for machine tools can be established, and estimates of the variability across different machine types generated. Furthermore, in-depth studies on sub-process level will lead to identification of process improvement opportunities directly related to the architecture and control logic of the investigated machine tools. The collected data for a broad range of manufacturing unit processes will lead to an extensive unit manufacturing process database which can be used by LCA experts, eco-designers and product developers for analysing the environmental impact of individual manufacturing unit processes as well as complete production chains. Finally, the ability to include the production phase in product life cycle studies will be greatly enhanced by completing the $CO_2$PE! UPLCI taxonomy.

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